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Prolonging fuel cell stack lifetime based on Pontryagin's Minimum Principle in fuel cell hybrid vehicles and its economic influence evaluation

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HIGHLIGHTS

- Power management strategy for prolonging fuel cell stack lifetime in FCHVs.
- The strategy brings trade-off between fuel cell lifetime and fuel consumption.
- Positive economic influence of the proposed strategy is finally proved.

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ABSTRACT

The lifetime of fuel cell stacks is a major issue currently, especially for automotive applications. In order to take into account the lifetime of fuel cell stacks while considering the fuel consumption minimization in fuel cell hybrid vehicles (FCHVs), a Pontryagin's Minimum Principle (PMP)-based power management strategy is proposed in this research. This strategy has the effect of prolonging the lifetime of fuel cell stacks. However, there is a tradeoff between the fuel cell stack lifetime and the fuel consumption when this strategy is applied to an FCHV. Verifying the positive economic influence of this strategy is necessary in order to demonstrate its superiority. In this research, the economic influence of the proposed strategy is assessed according to an evaluating cost which is dependent on the fuel cell stack cost, the hydrogen cost, the fuel cell stack lifetime, and the lifetime prolonging impact on the fuel cell stack. Simulation results derived from the proposed power management strategy are also used to evaluate the economic influence. As a result, the positive economic influence of the proposed PMP-based power management strategy is proved for both current and future FCHVs.

1. Introduction

Fuel cell hybrid vehicles (FCHVs) can achieve higher energy efficiency and lower emission compared to conventional vehicles. They have become a major topic of interest in academia and in the automotive industry owing to the energy supply problem and environmental problems [1]. Though a lot of research efforts have been made in order to bring fuel cell vehicles to daily life, high-volume production of fuel cell vehicles is still impossible using current technology. Cost and durability problems of fuel cell stacks are generally regarded as the main challenges to commercialization of fuel cell vehicles [2–4]. The most expensive part of a fuel cell stack is the platinum, which is used as a catalyst, bipolar plates, and a proton exchange membrane [5]. Previous research [6] presented that approximately 90% of production cost at high production rates is for material in a fuel cell stack. The cost problem of fuel cell stacks can be solved by increasing the power density of the stacks, decreasing the

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platinum loading of the electrodes, decreasing the platinum market price, and high-volume production. Technologies and policies related to the cost problem need to be further improved. The lifetime of a fuel cell is assessed by the number of hours until 10% power is lost [3,7]. With regard to the lifetime (durability) of fuel cell stacks, the US Department of Energy (DOE) has set the target of 5000 h for light-weight vehicles [8–10] and Ford Motor Company has established the commercial target of 6000–8000 h [11]. Although United Technologies Corporation (UTC) reported that its 120 kW fuel cell system operated for 7000 h without changing any subsystems [12], most fuel cells fall short of meeting the DOE target currently. In recent research, the lifetime of fuel cell vehicles is defined as 1700 h [13] and 2000 h [14]. The lifetime of fuel cell stacks is affected by many internal and external factors, such as fuel cell design and assembly, degradation of materials, operating conditions, and impurities or contaminants [8]. For automotive applications, the fuel cell stacks undergo complex operating conditions, such as start–stop condition and frequent load changing condition. This is the primary reason why the lifetime of automotive fuel cell stacks is shorter than that of stationary fuel cell stacks [15,16]. For FCHVs, the operating condition of fuel cell stacks can be improved by properly distributing the power requirement among power sources. This is one of the advantages of power source hybridization. The power distribution is related to power management strategies in hybrid vehicles.

Currently, the power management strategies can be classified into two major groups: one is based on the heuristic concept and the other is based on the optimal control theory. The former mainly indicates those strategies based on some control rules, such as rule-based algorithms and fuzzy logic algorithms [17,18]. These types of strategies are relatively simple but cannot guarantee the optimal fuel economy. To remedy this problem, the optimal control theory was introduced as part of the power management strategy of hybrid vehicles, including both Dynamic Programming (DP) [17] and Pontryagin's Minimum Principle (PMP) [19,20]. Although the DP approach guarantees global optimality when the driving cycle information is given in advance, it cannot be used directly for the real-time control of hybrid vehicles because of the long calculation time. The PMP-based power management strategy optimizes the power distribution by instantaneously providing the necessary optimality conditions. One of the major advantages of the PMP-based strategy is that there is usually only one parameter to be tuned in this strategy in order to obtain optimal results over a specific driving cycle [19]. Moreover, the core of this strategy is implementable in a real-time controller [20].

In this research, a PMP-based power management strategy is proposed for FCHVs. This strategy takes into account the fuel cell stack lifetime and the fuel economy at the same time. The fuel cell stack lifetime can be prolonged, given that the optimal trajectory of the fuel cell system (FCS) net power becomes smooth by this strategy. However, simulation results show that there is a tradeoff between the fuel cell stack lifetime and the fuel consumption when this strategy is adopted. The positive economic influence of this strategy needs to be verified in order to demonstrate its superiority. In this research, the economic influence of the proposed PMP-based strategy is analyzed and evaluated based on the fuel cell stack cost, the hydrogen cost, the fuel cell stack lifetime, the lifetime prolonging impact on the fuel cell stack, and simulation results derived from the proposed strategy. Several different reference values for the costs and the lifetime are introduced when evaluating the economic influence.

The outline of this paper is organized as follows: in Section 2, the proposed PMP-based power management strategy is introduced and the simulation results of the proposed strategy when it is applied to an FCHV are provided; in Section 3, the economic influence of the proposed strategy is evaluated by a defined parameter and based on some reference values; finally, discussions are presented in Section 4 and conclusions are drawn from this research in Section 5.

2. PMP-based power management strategy considering fuel cell stack lifetime

The PMP is a part of the optimal control theory [21]. The PMP-based power management strategy instantaneously provides necessary conditions to optimal control problems to let them find optimal control laws. Previously, some researchers have studied this type of optimal control strategy for hybrid vehicles [19,22,23]. In earlier research on the PMP-based power management strategy, the control problem's performance measure to be minimized was the total fuel consumption, the state variable of the control system was the battery state of charge (SOC), and the control variable was the battery power or the engine power or the FCS net power. Some researchers have extended the basic form of the optimal control problem by adding state variables or cost functions in order to achieve some specific goals [24–26]. In our previous research [1,27,28], the PMP-based power management strategy for FCHVs was presented. Among them, the strategy which takes into account the fuel cell stack lifetime was simply introduced in the research [28]. In this section, this strategy is introduced specifically and the simulation results are also provided.

2.1. Control problem formulation

In this research, the objective of the optimal control problem is to find the optimal power split trajectory when the FCHV is being driven, which minimizes the fuel consumption while takes into account the fuel cell stack lifetime. This problem is solved by searching for the optimal trajectory of the FCS net power, which is the control variable of the control system. The battery SOC is the state variable of the control system, and the state equation which expresses the dynamic behavior of the battery is as follows:

$$\dot{\mathrm{SOC}}(t) = F\left(\mathrm{SOC}(t), P_{\mathrm{fcs}}(t)\right) \tag{1}$$

In this equation, P_{fcs} represents the FCS net power. It replaced the battery power here, as the required power for the vehicle is provided at every moment.

As stated previously, restricting dynamics of the load has an effect of prolonging the fuel cell stack lifetime [15,16]. Many researchers have analyzed the degradation mechanism of fuel cells and have pointed that the load dynamics affects the durability of fuel cells [13,29]. Previous research [30] investigated the effect of dynamic driving cycle on the performance degradation of fuel cells for automotive applications. Also, previous research [15] studied the relationship between load changing operation and fuel cell lifetime when presenting a quick evaluating method for automotive fuel cell lifetime. The load dynamics of an FCS influences its power changing rate, thus a limitation value was set on the power changing rate of the FCS when developing power management strategies for FCHVs in the previous research [31–33]. In this research, a cost function L is defined and introduced to the optimal control problem in order to avoid frequent and rapid changes of the dynamic load of the FCS, as follows:

$$L\left(P_{\mathrm{fcs}}(t)\right) = a \cdot \left(P_{\mathrm{fcs}}(t) - P_{\mathrm{fcs}}(t-b)\right)^2 \tag{2}$$

Here, a is a tuning parameter, t represents a time step, $t-b$ represents its previous time step, and b is the duration of one time

step. This new cost function is related to the power changing rate of the FCS.

Considering the fuel consumption and the fuel cell stack lifetime and the state equation (1), which is a constraint of the optimal control problem, the performance measure to be minimized when an FCHV drives over a specified driving cycle from time t_0 to time t_f is as follows:

$$J\left(P_{fcs}(t)\right) = \int_{t_0}^{t_f}\left\{\dot{m}_{h_2}\left(P_{fcs}(t)\right) + L\left(P_{fcs}(t)\right) + p(t)\cdot\left(F\left(SOC(t), P_{fcs}(t)\right) - \dot{S}OC(t)\right)\right\}dt \quad (3)$$

In this equation, J is the performance measure which depends on the control variable P_{fcs}. $\dot{m}_{h_2}$ represents the fuel consumption rate of the FCS, which has a relationship with the FCS net power. Details on their relationship can be found in our previous research [1,27]. p is called the costate in the PMP.

According to the optimal control theory based on the Calculus of Variation, the optimal solution of the control problem here can be obtained when the variation of the performance measure δJ is zero [21], as follows:

Table 1
Parameters of the vehicle.

Item	Value
Vehicle total mass (kg)	1700
Final drive gear efficiency (%)	95
Tire radius (m)	0.29
Aerodynamic drag coefficient	0.37
Vehicle frontal area (m^2)	2.59
Air density (kg m^{-3})	1.21
Rolling resistance coefficient	0.014

Details on the derivation process of (6) can be found in the literature [21]. The necessary conditions in (6) should be satisfied all the time. The first necessary condition is the state equation (1); The second necessary condition is the costate equation, which provides the condition of determining the optimal trajectory of the costate p when its initial value is given; The third necessary condition determines the optimal trajectory of the control variable P_{fcs} by searching for the control variable among available control variables that minimizes the Hamiltonian at every calculation time step. Details on the derivation process of optimal solution from the necessary condition (6) can be found in our previous research [27].

$$\begin{aligned}\delta J &= 0\\ &= \int_{t_0}^{t_f+\delta t_f}\left\{\dot{m}_{h_2}\left(P_{fcs}+\delta P_{fcs}\right) + L\left(P_{fcs}+\delta P_{fcs}\right) + p\cdot\left(F\left(SOC+\delta SOC, P_{fcs}+\delta P_{fcs}\right) - \left(\dot{SOC}+\delta\dot{SOC}\right)\right)\right\}\\ &\quad dt - \int_{t_0}^{t_f}\left\{\dot{m}_{h_2}\left(P_{fcs}\right) + L\left(P_{fcs}\right) + p\cdot\left(F\left(SOC, P_{fcs}\right) - \dot{SOC}\right)\right\}dt\end{aligned} \quad (4)$$

If introduce a Hamiltonian H, which is defined as,

$$H\left(SOC(t), P_{fcs}(t), p(t)\right) = \dot{m}_{h_2}\left(P_{fcs}(t)\right) + L\left(P_{fcs}(t)\right) + p(t)\cdot F\left(SOC(t), P_{fcs}(t)\right) \quad (5)$$

then necessary conditions of the optimal solution derived from (3), (4), and (5) are as follows:

It can be observed from (2), (5) and the third necessary condition in (6) that the cost function L affects the determination of the optimal FCS net power at every calculation time step. Consequently, the definition of the cost function L will make the optimal trajectory of the FCS net power smooth. In this control problem formulation, the optimal solution is dependent on the tuning parameter a.

2.2. Simulation results

In this subsection, the PMP-based power management strategy introduced in Subsection 2.1 is applied to an FCHV in a computer simulation environment and the simulation results are presented. The vehicle parameters used in this research are shown in Table 1.

$$\begin{aligned}&\dot{SOC}^*(t) = \frac{\partial H}{\partial p}\left(SOC^*(t), P^*_{fcs}(t), p^*(t)\right) = F\left(SOC^*(t), P^*_{fcs}(t)\right)\\ &\dot{p}^*(t) = -\frac{\partial H}{\partial SOC}\left(SOC^*(t), P^*_{fcs}(t), p^*(t)\right) = -p^*(t)\cdot\frac{\partial F}{\partial SOC}\left(SOC^*(t), P^*_{fcs}(t)\right)\\ &H\left(SOC^*(t), P^*_{fcs}(t), p^*(t)\right) \le H\left(SOC^*(t), P_{fcs}(t), p^*(t)\right)\end{aligned} \quad (6)$$

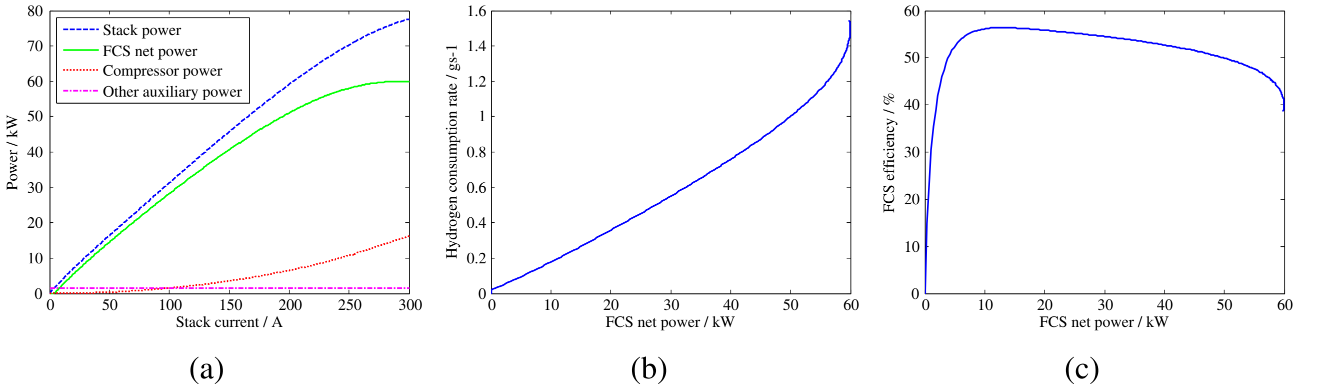

Fig. 1. Characteristics of the FCS used in this research: (a) stack-provided power, auxiliary power, and net power of the FCS, (b) relationship between the FCS net power and the fuel consumption rate of the FCS, (c) efficiency map of the FCS.

Parts of these data are sourced from available literature [31]. In this research, a 60 kW FCS and a battery with the energy capacity of 1.5 kWh are selected as power sources of the FCHV. Figs. 1 and 2 illustrate the information of the FCS and the battery selected in this research, respectively. The FCS model is constructed based on the previous research [34,35]. In this FCS model, the main losses of a single cell are considered by physical and empirical equations. The power loss caused by an air compressor is modeled by a map which is obtained from the compressor model, and the part of power loss caused by other auxiliary components is assumed to be a constant. The lower heating value of hydrogen is used when calculating the FCS efficiency. The internal resistance model of the battery is used in this research. Details on the two power sources can refer to our previous research [28]. A 75 kW motor is also selected which uses a map to express its efficiency.

In order to evaluate the proposed power management strategy, simulation results for the case where the fuel cell stack lifetime is not taken into account and for the case where it is considered by the cost function L are compared. Here, the former indicates the PMP-based power management strategy before the cost function L is introduced, which is also named as the basic strategy in this research. The basic strategy was introduced by some researchers and can also be found in our previous research [27,28]. The basic strategy does not contain those terms related to the cost function L in Equations (3)–(6). For example, (3) and (5) will take the forms of (7) and (8). Consequently, the optimal solution of the basic strategy is obtained based on the necessary conditions considering only the fuel consumption minimization. Therefore, the basic strategy does not take into account the fuel cell stack lifetime.

$$J\left(P_{\mathrm{fcs}}(t)\right) = \int_{t_0}^{t_f} \left\{ \dot{m}_{h_2}\left(P_{\mathrm{fcs}}(t)\right) + p(t)\cdot\left(F\left(\mathrm{SOC}(t), P_{\mathrm{fcs}}(t)\right) - \dot{\mathrm{SOC}}(t)\right)\right\} \mathrm{d}t \tag{7}$$

$$H\left(\mathrm{SOC}(t), P_{\mathrm{fcs}}(t), p(t)\right) = \dot{m}_{h_2}\left(P_{\mathrm{fcs}}(t)\right) + p(t)\cdot F\left(\mathrm{SOC}(t), P_{\mathrm{fcs}}(t)\right) \tag{8}$$

Figs. 3–5 illustrate the comparison results on the FTP72 urban driving cycle, NEDC 2000, and Japan 1015 driving cycle, respectively. The initial battery SOC and the final SOC are both 0.6 here. These figures indicate that the optimal trajectory of the FCS net power becomes smooth when the proposed PMP-based power management strategy is applied. Thus, the fuel cell stack lifetime can be prolonged by the proposed strategy.

Table 2 lists the simulation result on the fuel consumption for the two strategies when the tuning parameter a is 0.002. The fuel cell stack lifetime can be prolonged by the proposed power management strategy. However, it can also be observed from Table 2 that the fuel consumption is increased in this case. The economic influence of the proposed strategy should be analyzed, as there is a

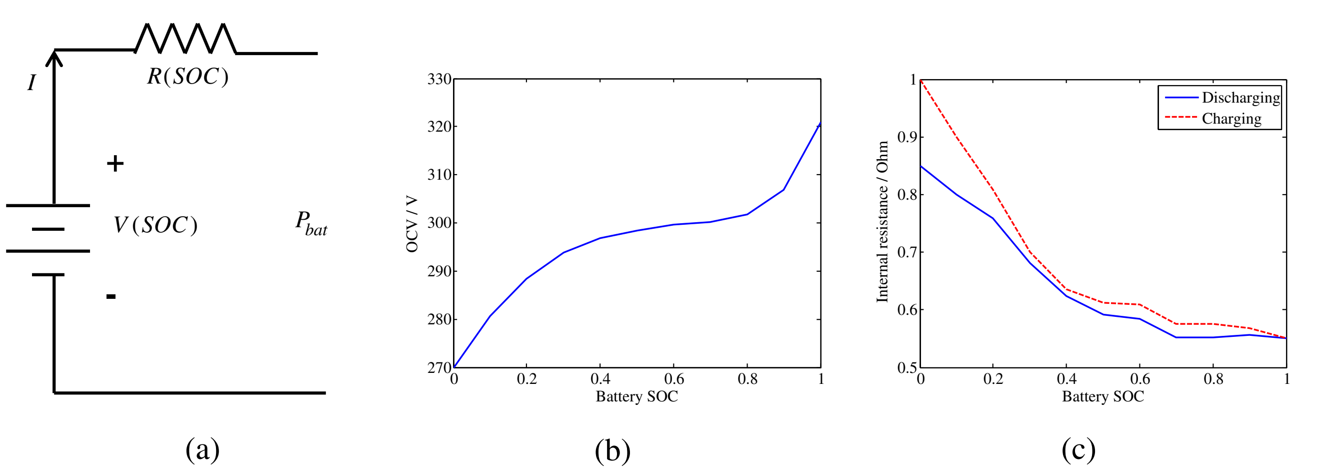

Fig. 2. Characteristics of the battery used in this research: (a) electrical schematic of the battery model, (b) OCV of the battery, (c) internal resistance of the battery.

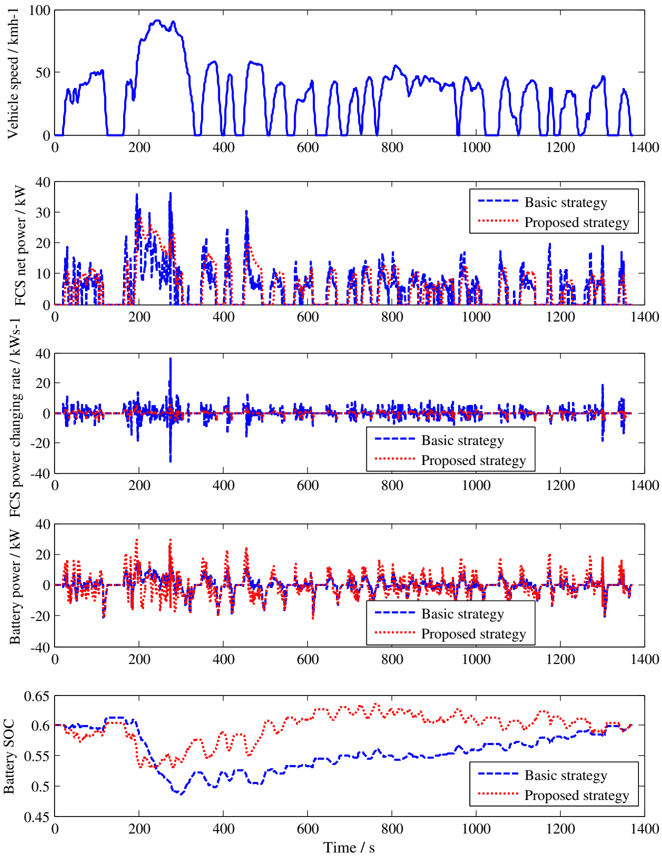

Fig. 3. Simulation results comparison on the FTP72 urban driving cycle.

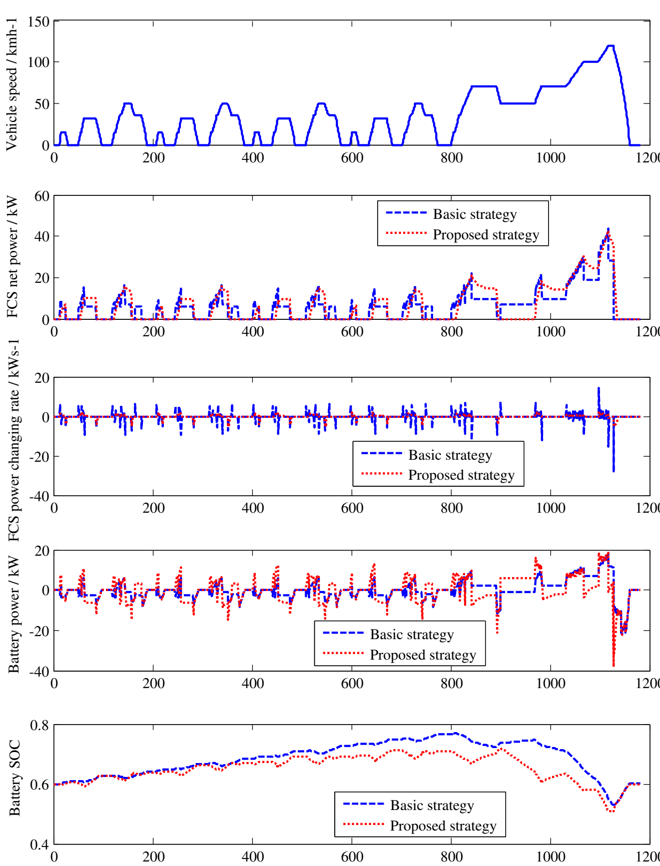

Fig. 4. Simulation results comparison on the NEDC 2000.

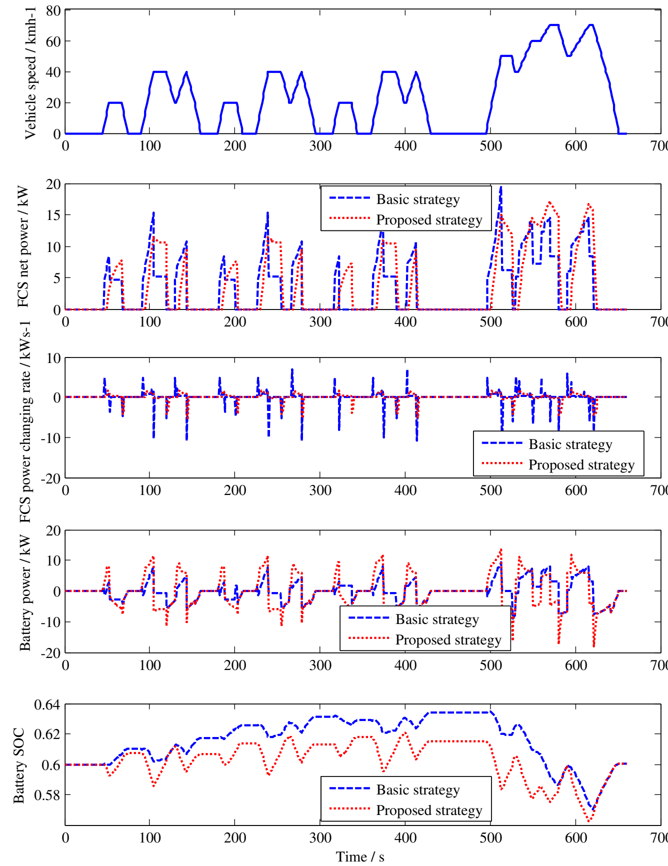

Fig. 5. Simulation results comparison on the Japan 1015 driving cycle.

tradeoff between the fuel consumption and the fuel cell stack lifetime when this strategy is applied.

3. Economic influence evaluation of the proposed PMP-based power management strategy

In this section, the economic influence of the proposed strategy is analyzed for the FCHV based on the fuel cell stack cost, the hydrogen cost, the fuel cell stack lifetime, the lifetime prolonging impact of the proposed strategy, and the simulation results of the proposed strategy. In order to determine the costs, the lifetime, and the lifetime prolonging impact, a review of publications in the literature is firstly carried out and appropriate values are selected as references.

3.1. Determination of the fuel cell stack cost, the hydrogen cost, the fuel cell stack lifetime, and the lifetime prolonging impact

3.1.1. Fuel cell stack cost determination

In this research, the fuel cell stack cost is divided into current and future costs. It is assumed that high-volume production of the

Table 2
Fuel consumption of the proposed strategy and the basic strategy.

Driving cycle	Fuel consumption (kg per 100 km)	
	Basic strategy	Proposed strategy
FTP72 urban	1.153	1.207
NEDC 2000	1.286	1.331
Japan 1015	1.125	1.169

Table 3
Costs, lifetime, and growth factor used in this research.

	Current	Future
Fuel cell stack cost ($ kW^{-1})	1000–1500	12–202
Hydrogen cost ($ kg^{-1})	3.41, 3.86, 8.50	2.96, 3.08, 6.72
Fuel cell stack lifetime (h)	1500–2500	5000–6000
Lifetime growth factor	FTP72 urban: 3.35, 3.61, 4.08, 4.30, 4.48 NEDC 2000: 2.76, 3.00, 3.21, 3.75 Japan 1015: 1.65, 1.69, 5.00	

fuel cell stack for automotive applications is possible in the future, and thus the production cost in the future will be much lower than current. The DOE's cost target of the fuel cell stack is 25 $ kW^{-1} for 2010 and is 15 $ kW^{-1} for 2015 [2]. Previous research [3] presented that the fuel cell system cost could be brought down to 61 $ kW^{-1} (27 $ kW^{-1} for stack) in 2009 if high-volume production was possible. In the research [5], it is assumed based on a literature review that the fuel cell stack cost is 1200 ± 200 € kW^{-1} for current case and is 110 ± 49 € kW^{-1} for future case. In the research [6], a detailed cost evaluation of the fuel cell stack is carried out for high production rates at approximately 0.5 million vehicles per year. This information, together with the cost information on the fuel cell stack for very low production rates, is used to derive necessary learning curve rates. Assuming that technical aspects of the fuel cell stack will further improve and platinum price will return to its past mean value, the learning curve reflects that the fuel cell stack cost starts at approximately 1000 $ kW^{-1} for 100 vehicles and decreases to approximately 12–40 $ kW^{-1} for 1 million vehicles produced. According to above review, the cost range of the fuel cell stack for both current and future cases is determined as listed in Table 3.

3.1.2. Hydrogen cost determination

The hydrogen production method will be improved in the future, thus the hydrogen cost is also considered for current and future cases in this research. In the research [5,36], the cost of production and distribution of the hydrogen from coal is estimated at 4.5 € kg^{-1} as of 2020. In the research [37], a reference value of 20 RMB kg^{-1} is used as the hydrogen price when discussing the optimal sizing of a plug-in fuel cell hybrid vehicle. Previous research [38] has presented the hydrogen costs for different supply options on both current and future technologies. The supply options provided are onsite electrolysis, onsite steam methane reforming (SMR), and central SMR. In our research, the last reference is employed as listed in Table 3.

3.1.3. Fuel cell stack lifetime determination

The fuel cell stack lifetime depends on many internal and external factors, and there is a large gap between the target and the current status, thus the fuel cell stack lifetime is also considered for current and future cases in this research. The US DOE has set 5000 h of operational lifetime for proton exchange membrane (PEM) fuel cell stacks in automotive applications [8–10]. However, this is hardly achievable for today's fuel cell technology. In the previous research, the lifetime of fuel cell vehicles was defined as around 1700 h [13] and 2000 h [14]. Previous research [3] stated that a fuel cell lifetime of ~2500 h was achieved in 2009 for transportation. According to above review, the lifetime range of the fuel cell stack for both current and future cases is determined as listed in Table 3.

3.1.4. Lifetime prolonging impact determination

In the research [15], a quick evaluating method for automotive fuel cell stack lifetime is presented. According to the research,

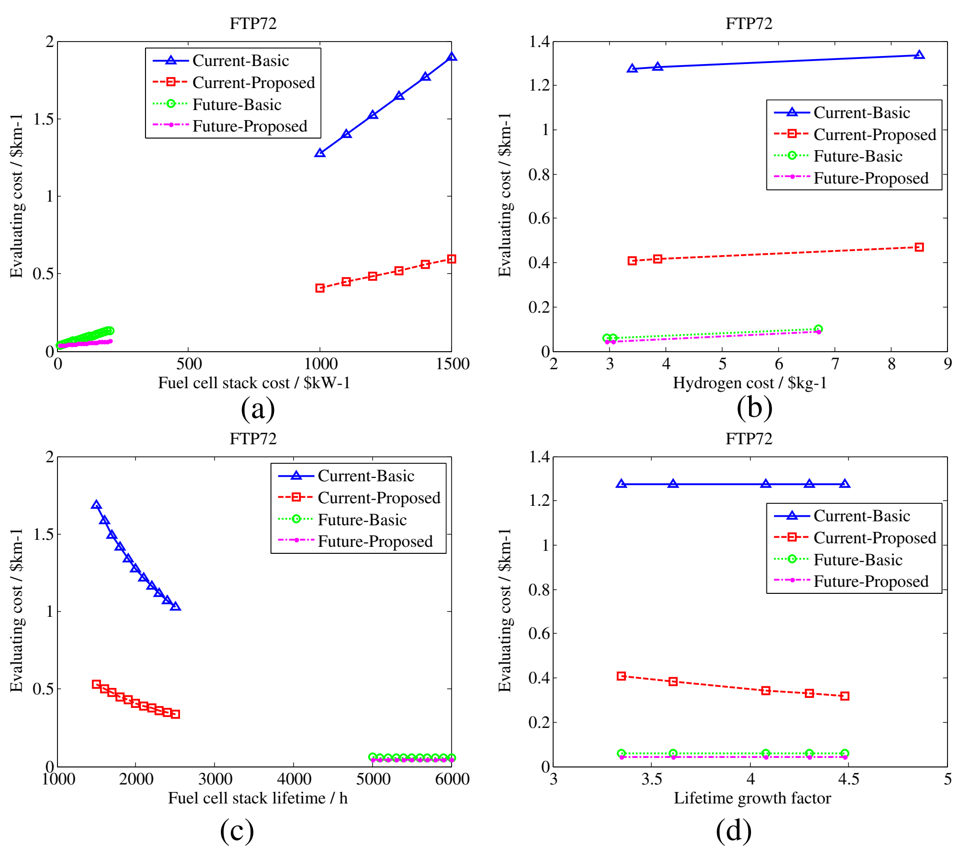

Fig. 6. Evaluating cost on the FTP72 urban driving cycle for both current and future cases: (a) for different fuel cell stack cost, (b) for different hydrogen cost, (c) for different fuel cell stack lifetime, (d) for different lifetime growth factor.

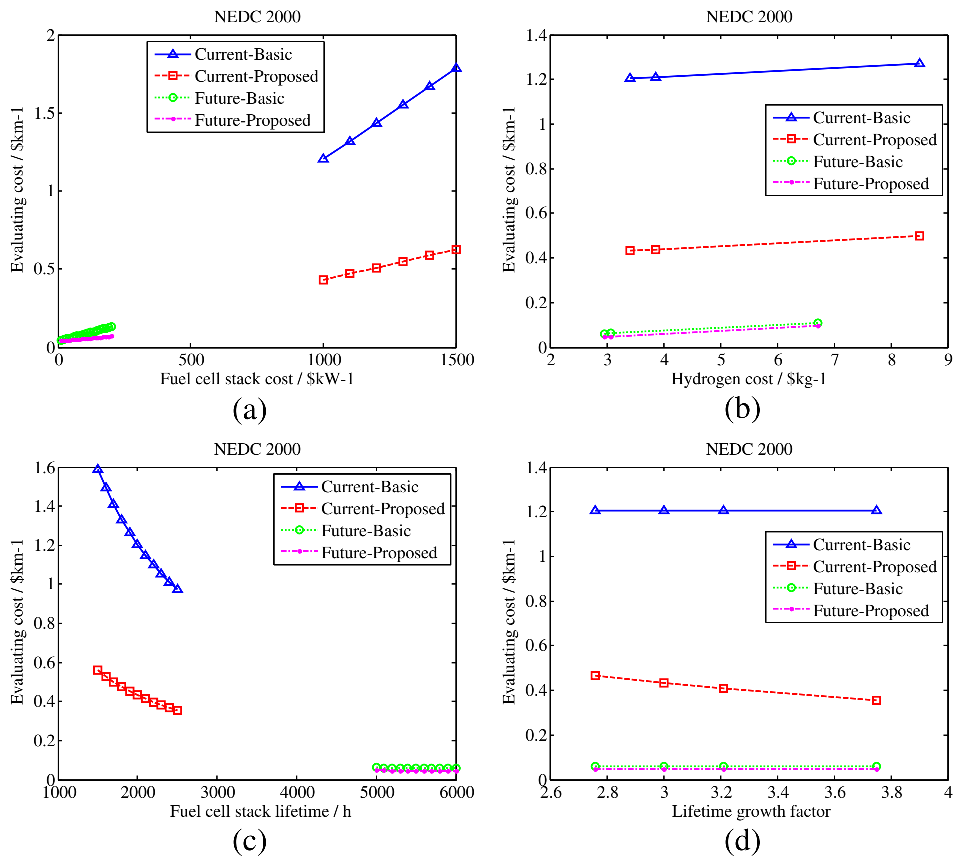

Fig. 7. Evaluating cost on the NEDC 2000 for both current and future cases: (a) for different fuel cell stack cost, (b) for different hydrogen cost, (c) for different fuel cell stack lifetime, (d) for different lifetime growth factor.

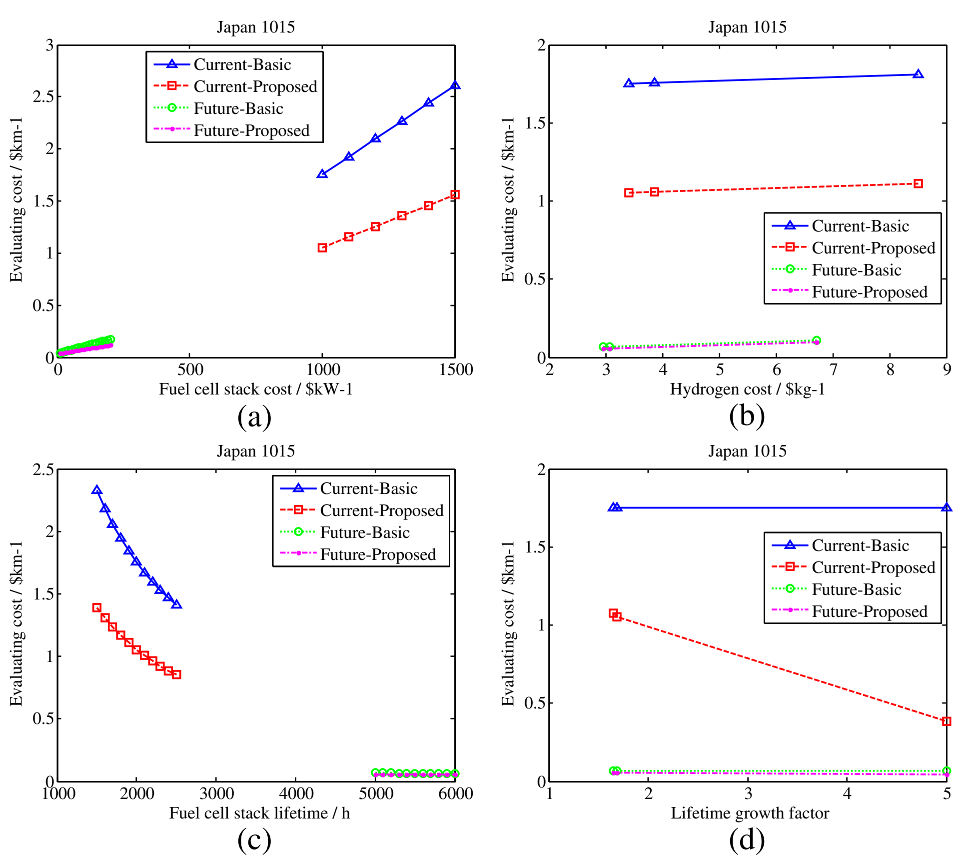

Fig. 8. Evaluating cost on the Japan 1015 driving cycle for both current and future cases: (a) for different fuel cell stack cost, (b) for different hydrogen cost, (c) for different fuel cell stack lifetime, (d) for different lifetime growth factor.

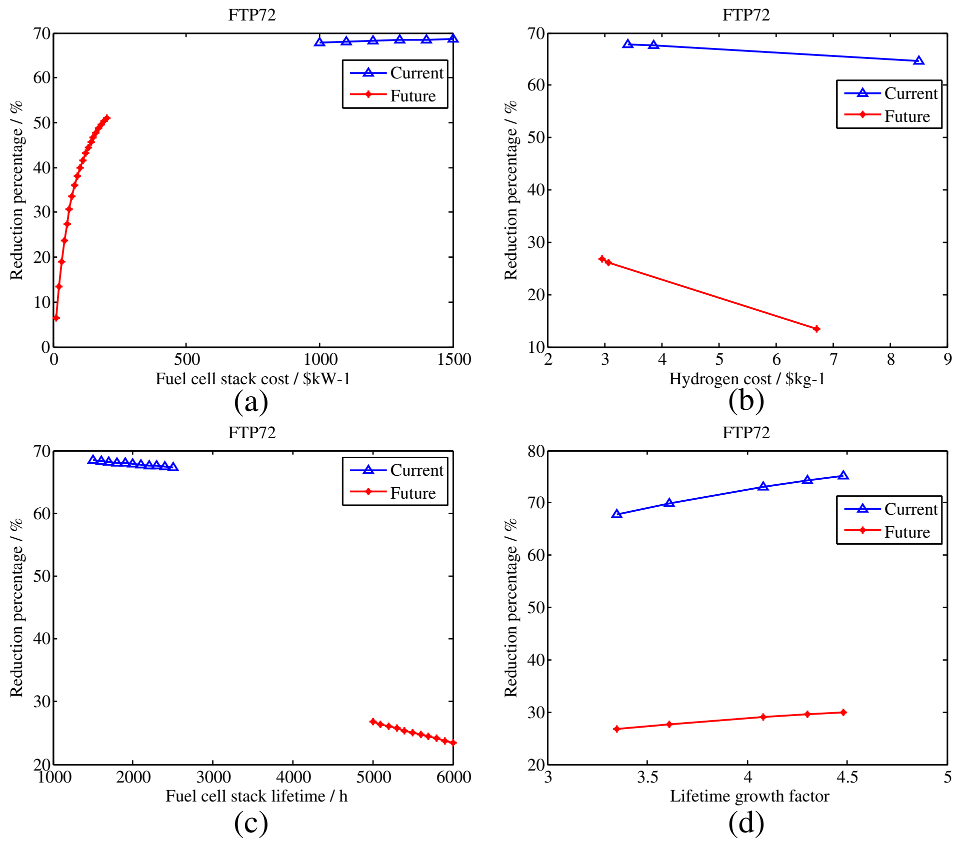

Fig. 9. Reduction percentage on the FTP72 urban driving cycle for both current and future cases: (a) for different fuel cell stack cost, (b) for different hydrogen cost, (c) for different fuel cell stack lifetime, (d) for different lifetime growth factor.

performance degradation of a fuel cell stack is linear with time, and the fuel cell stack lifetime can be given by the following equation.

$$T_f = \frac{\Delta P}{k_p \cdot (p_1' \cdot n_1 + p_2' \cdot n_2 + p_3' \cdot t_1 + p_4' \cdot t_2)} \tag{9}$$

In this equation, ΔP is the limited decreasing value of the fuel cell stack performance from beginning to the lifetime end (generally 10%), k_p is the accelerating coefficient caused by the difference between laboratory and road tests. p_1', p_2', p_3', and p_4' represent performance deteriorate rates of the fuel cell stack resulted from large-range load change cycling, start–stop cycling, idle condition, and high power load condition, measured in laboratory. n_1, n_2, t_1, and t_2 represent load changing cycle times, start–stop cycle times, idle time, and high power load time per hour, gained from vehicular driving cycle.

Among the four factors above, the load change cycling and the start–stop cycling are the main factors leading to the fuel cell stack performance decay. In the research [15], the two factors respectively possess 56% and one third of the entire deterioration on a driving cycle. In our research, the high power load condition is left out of consideration, and the idle condition can be ignored, as it has only a minor impact on the fuel cell stack performance degradation. Additionally, according to the research [15], the impact of the start–stop cycling on the fuel cell stack lifetime can be almost neglected when the stack open circuit voltage (OCV) is dispelled quickly after operation. Thus, only the load change cycling impact is taken into account in our research. In this case, Equation (9) can be transformed into the following equation.

$$T_f = \frac{\Delta P}{k_p \cdot p_1' \cdot n_1} \tag{10}$$

Here, ΔP and k_p are constants for a specific fuel cell stack; p_1' is also a constant when the load changing of the fuel cell stack is defined; n_1 is dependent on the definition of the load changing. In other words, for a given fuel cell stack, its lifetime only depends on n_1 when the load changing of the fuel cell stack is defined. Thus, the relationship between the value of n_1 under the proposed power management strategy and the value of n_1 under the basic strategy can be used to determine the lifetime prolonging impact on the fuel cell stack when the proposed strategy is applied.

In the research [15], the fuel cell stack load changing is defined as from idling condition to rated power condition. In this research, the power changing rate of the fuel cell stack and some different reference values are adopted with regard to the fuel cell stack load changing in order to more generally consider the load changing. The lifetime prolonging impact on the fuel cell stack is determined as follows:

(1) Calculate the power changing rate of the fuel cell stack dP_{stack}/dt every second when the proposed PMP-based power management strategy is applied to the FCHV.
(2) Record exceeding times of the power changing rate, $n_{1/proposed}$, from step (1) when a reference value is given.
(3) Repeat the same process of step (1) when the basic strategy is applied to the FCHV.
(4) Record exceeding times of the power changing rate, $n_{1/basic}$, from step (3) for the same reference value with step (2).
(5) According to Equation (10), a lifetime growth factor is defined as follows, which indicates the lifetime prolonging impact.

$$\alpha = T_{f/proposed}/T_{f/basic} = n_{1/basic}/n_{1/proposed} \tag{11}$$

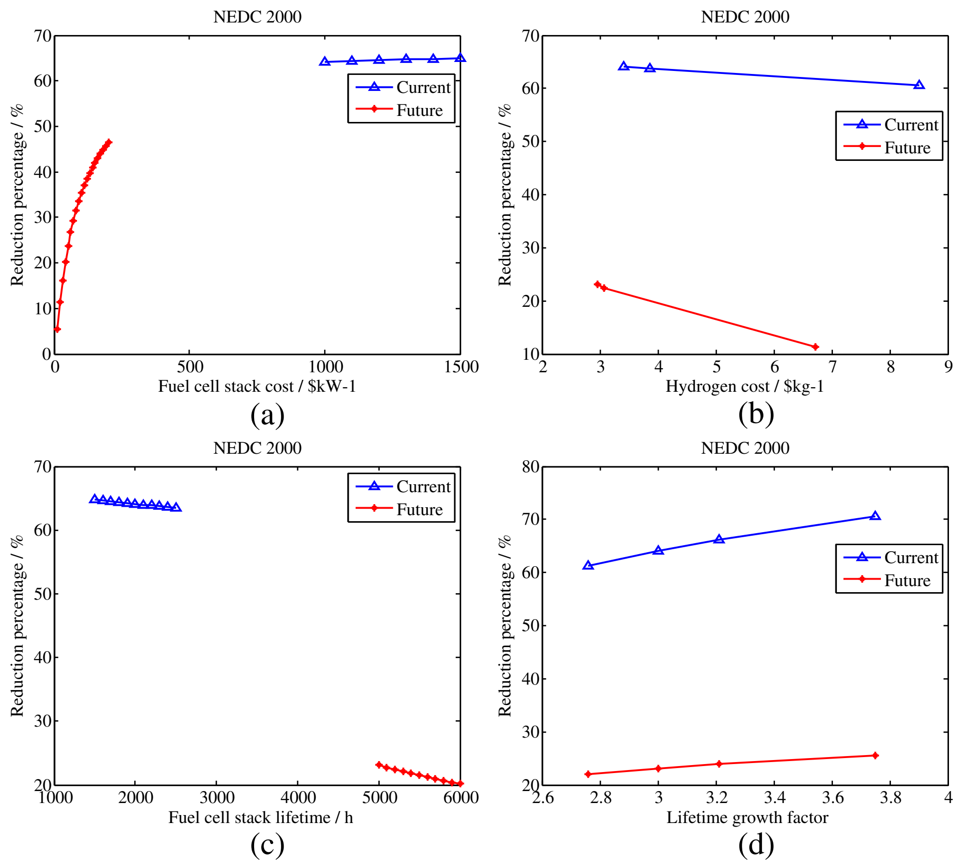

Fig. 10. Reduction percentage on the NEDC 2000 for both current and future cases: (a) for different fuel cell stack cost, (b) for different hydrogen cost, (c) for different fuel cell stack lifetime, (d) for different lifetime growth factor.

Here, $T_{f/\text{proposed}}$ is the fuel cell stack lifetime when the proposed strategy is applied and $T_{f/\text{basic}}$ is that when the basic strategy is applied. According to the above explanations, the lifetime growth factor is dependent on the selected reference value in the step (2) and step (4). For a driving cycle, different reference values can be selected to obtain different lifetime growth factors. For different driving cycles, the selected reference values are different depending on the driving cycle characteristics. Considering different reference values, the lifetime growth factors are selected as listed in Table 3. The reference values are 2.0 kW s^{-1}, 2.1 kW s^{-1}, 2.2 kW s^{-1}, 2.3 kW s^{-1}, 2.4 kW s^{-1} for the FTP72 urban driving cycle and 1.5 kW s^{-1}, 1.6 kW s^{-1}, 1.7 kW s^{-1}, 1.8 kW s^{-1} for the NEDC 2000 and 1.4 kW s^{-1}, 1.6 kW s^{-1}, 3.2 kW s^{-1} for the Japan 1015 driving cycle.

3.2. Economic influence evaluation of the proposed power management strategy

In this research, the economic influence of the proposed power management strategy is assessed by an evaluating cost which is defined as follows:

$$\text{EC} = \frac{C_{\text{stack}} + C_{\text{fuel}}}{D} \tag{12}$$

In this equation, EC represents the evaluating cost, C_{stack} represents the fuel cell stack cost. C_{fuel} and D are the hydrogen cost and the driving distance during the entire lifetime of the stack, respectively. For the basic strategy and the proposed PMP-based power management strategy, the evaluating cost can be expressed as follows:

$$\begin{aligned} \text{EC}_{\text{basic}} &= \frac{C_{\text{stack}} + \dot{m}_{\text{basic}} \cdot D_{\text{basic}} \cdot c_{\text{fuel}}}{D_{\text{basic}}} \\ EC_{\text{proposed}} &= \frac{C_{\text{stack}} + \dot{m}_{\text{proposed}} \cdot D_{\text{proposed}} \cdot c_{\text{fuel}}}{D_{\text{proposed}}} = \frac{C_{\text{stack}} + \dot{m}_{\text{proposed}} \cdot \alpha \cdot D_{\text{basic}} \cdot c_{\text{fuel}}}{\alpha \cdot D_{\text{basic}}} \end{aligned} \tag{13}$$

Here, the subscript basic corresponds to the basic strategy, and proposed corresponds to the proposed PMP-based power management strategy. $\dot{m}$ represents the fuel consumption per unit distance, which is listed in Table 2. c_{fuel} is the hydrogen cost per unit mass, and α is the lifetime growth factor defined in Equation (11).

It can be observed from Equation (13) that the evaluating cost depends on the fuel cell stack cost, the hydrogen cost, the fuel cell stack lifetime, the lifetime growth factor, and the fuel consumption rate. In this subsection, the evaluating cost of the proposed PMP-based power management strategy is compared to that of the basic strategy based on the selected reference values provided in Subsection 3.1 and the simulation results. Fig. 6 illustrates the comparison result of the evaluating cost on the FTP72 urban driving cycle for different fuel cell stack costs, different hydrogen costs, different lifetime values, and different lifetime growth factors. This figure also contains the information on both current and future cases. The fuel consumption information listed in Table 2 is also used here. Figs. 7 and 8 correspond to the NEDC 2000 and the Japan 1015 driving cycle, respectively. It can be observed from these three figures that the evaluating cost line derived from the proposed PMP-based power management strategy is always located under the line derived from the basic strategy for both current and future cases. Thus, those three figures indicate the same fact that the evaluating cost of the proposed PMP-based power management

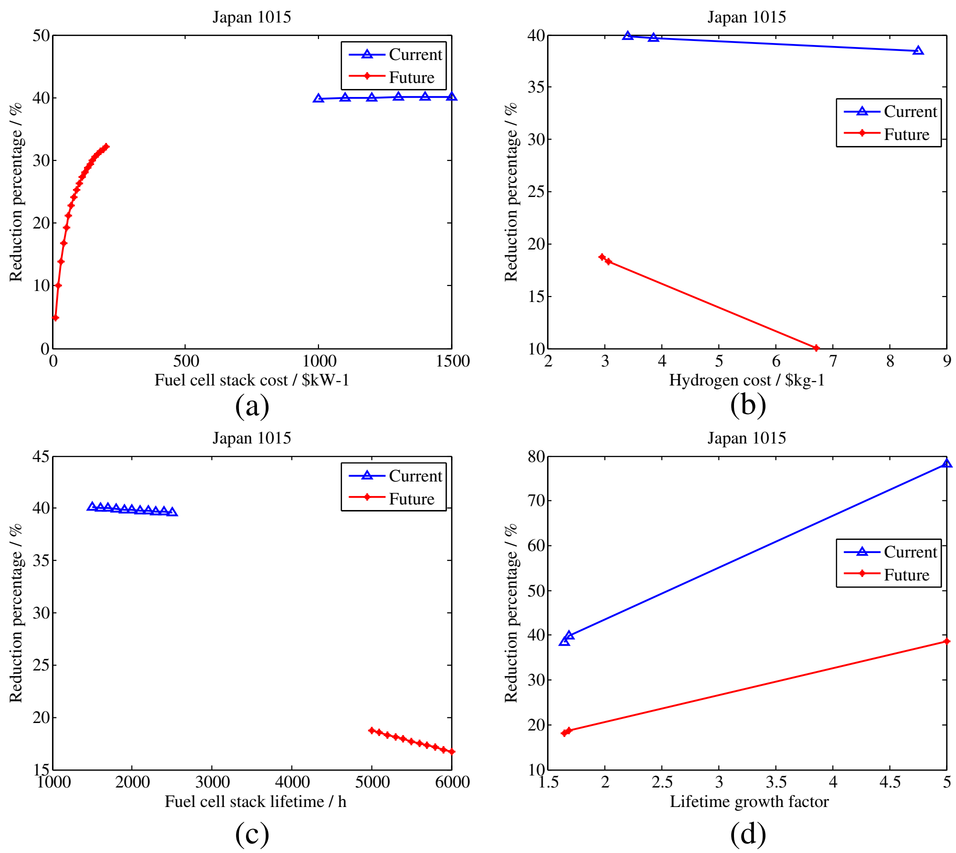

Fig. 11. Reduction percentage on the Japan 1015 driving cycle for both current and future cases: (a) for different fuel cell stack cost, (b) for different hydrogen cost, (c) for different fuel cell stack lifetime, (d) for different lifetime growth factor.

strategy is lower than that of the basic strategy for both current and future cases. Figs. 9–11 cover the information on the reduction of the evaluating cost when the proposed PMP-based power management strategy is adopted. The reduction percentage is defined as (14). Tables 4–7 respectively indicate the data information used in (a), (b), (c), and (d) of the six figures in this subsection.

$$\text{Percentage}_{\text{reduction}} = \frac{\text{EC}_{\text{Basic}} - \text{EC}_{\text{Proposed}}}{\text{EC}_{\text{Basic}}} \tag{14}$$

The above result proves the positive economic influence of the proposed PMP-based power management strategy for both current and future situations. This means the proposed strategy not only has the effect of prolonging the fuel cell stack lifetime but also has the ability to decrease the evaluating cost.

4. Discussion

The evaluating cost of the proposed PMP-based power management strategy is lower than that of the basic strategy, thus the

Table 4
Data used in the figure (a).

	Current	Future
Hydrogen cost ($ kg^{-1})	3.41	2.96
Fuel cell stack lifetime (h)	2000	5000
Lifetime growth factor	FTP72 urban: 3.35, NEDC 2000: 3.00, Japan 1015: 1.69	

Table 5
Data used in the figure (b).

	Current	Future
Fuel cell stack cost ($ kW^{-1})	1000	50
Fuel cell stack lifetime (h)	2000	5000
Lifetime growth factor	FTP72 urban: 3.35, NEDC 2000: 3.00, Japan 1015: 1.69	

Table 6
Data used in the figure (c).

	Current	Future
Fuel cell stack cost ($ kW^{-1})	1000	50
Hydrogen cost ($ kg^{-1})	3.41	2.96
Lifetime growth factor	FTP72 urban: 3.35, NEDC 2000: 3.00, Japan 1015: 1.69	

Table 7
Data used in the figure (d).

	Current	Future
Fuel cell stack cost ($ kW^{-1})	1000	50
Hydrogen cost ($ kg^{-1})	3.41	2.96
Fuel cell stack lifetime (h)	2000	5000

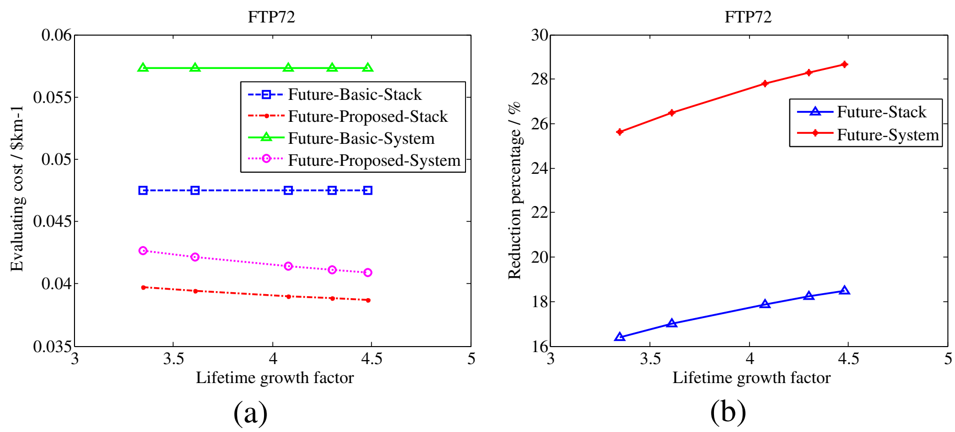

Fig. 12. Comparison between the case where the fuel cell stack cost is used and the case where the FCS cost is employed: (a) evaluating cost, (b) reduction percentage.

positive economic influence of the proposed PMP-based strategy is proved. Details on the six figures in Subsection 3.2 are as follows: The evaluating cost increases while the fuel cell stack cost increases and while the hydrogen cost increases for both basic and proposed strategies and for both current and future cases; The evaluating cost decreases while the fuel cell stack lifetime increases for both basic and proposed strategies and for both current and future cases; The evaluating cost decreases while the lifetime growth factor increases for the proposed strategy for both current and future cases; The reduction percentage increases when the fuel cell stack cost increases for both current and future cases, and it is more sensitive for future case; The reduction percentage decreases when the hydrogen cost increases and when the fuel cell stack lifetime increases for both current and future cases, and it is more sensitive for future cases; The reduction percentage increases when the lifetime growth factor increases for both current and future cases, and it is more sensitive for current case.

It can be observed from Figs. 9–11 that the reduction percentage line for current case is always located above that for future case. This indicates that the superiority of the proposed PMP-based power management strategy is more outstanding for current cases.

The battery aging is not considered in this research, as the cost of the fuel cell stack is very much higher than the battery's and the FCS is the primary power source of the FCHV. However, it should be taken into account when the fuel cell stack cost decreases to a level which is similar to the battery's level and the FCS is not the main power source.

In this research, the positive economic influence of the proposed PMP-based power management strategy is proved for an FCHV where the FCS is the primary power source. This is the general type of FCHV currently. For a special type of FCHV, for example a plug-in fuel cell vehicle with a large-capacity battery, the economic influence of the proposed strategy needs to be further discussed.

In this research, the fuel cell stack cost is used when calculating the evaluating cost as shown in (12) and (13). If the FCS cost (including auxiliary components) is employed, the reduction percentage in Figs. 9–11 will be higher. Fig. 12 provides the information on the evaluating cost and the reduction percentage for the case where the fuel cell stack cost is used and the case where the FCS cost is employed. A fuel cell stack cost of 27 $ kW^{-1} and an FCS cost of 61 $ kW^{-1} are used for reference [3]. The fuel cell stack size is 78 kW while the FCS size is 60 kW as shown in Fig. 1. The future data in Table 7 except the fuel cell stack cost are also used here. Fig. 12 illustrates that the evaluating cost is higher when the FCS cost is used instead of the fuel cell stack cost for both the basic strategy and the proposed strategy, and the reduction percentage is higher when the FCS cost is used.

5. Conclusion

In order to take into account the fuel cell stack lifetime while considering the fuel consumption minimization in FCHVs, the PMP-based power management strategy is proposed where the new cost function is introduced. The economic influence of the proposed strategy is assessed by the evaluating cost, and the superiority of the proposed strategy is proved by comparing its evaluating cost to the basic strategy's evaluating cost. The following two points are acquired from this research.

(1) By introducing the cost function L, the proposed PMP-based power management strategy has an effect of prolonging the fuel cell stack lifetime.
(2) There is a tradeoff between the fuel consumption and the fuel cell stack lifetime when the proposed strategy is applied. However, the evaluating cost comparison indicates that the proposed strategy decrease the evaluating cost compared to the basic strategy. Hence, this strategy is superior from both lifetime viewpoint and economic viewpoint.

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